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SALT NUCLEI, WIND AND DAILY RAINFALL IN HAWAII

By

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SALT NUCLEI, WIND AND DAILY RAINFALL IN HAWAII

A. H. Woodcock[1] and W. A. Mordy[2]

Abstract

The discovery of large sea-salt particles at cloud levels led to the hypothesis that these particles act as nuclei on which raindrops initially form within clouds and to the suggestion that the amount of rainfall on an oceanic island might be a function of the number of the salt particles in the air. Exploratory observations of rain and airborne salt in Hawaii, which were intended to test this suggestion, are presented and discussed. These observations do not prove that greater numbers of salt nuclei are related to greater amounts of rain. They do, however, in the author's opinion, indicate that such a relationship may exist and that a further more detailed field study should be made which utilizes the pertinent results of the present study.

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1. Woods Hole Oceanographic Institution. Work supported by the Office of Naval Research under contract Nonr-798 (00)(NR-085-001).

2. Meteorology Department, Pineapple Research Institute and Hawaiian Sugar Planters Association.

Introduction

The presence of large sea-salt particles at cloud heights (15) and the recent theoretical indications of the possible role of such particles in the growth of raindrops by accretion (2)(5)(7), caused us to suppose that the amount of rainfall might be related to the quantity of salt in the air. The physical basis for this supposition lies in the computations of the accretional growth of droplets made by Langmuir (5). These computations show that initially large cloud droplets should grow more rapidly than do smaller droplets. The amount of water removed from clouds by droplets falling through them might be expected therefore to be a function of the initial size of these larger droplets and of their number, other relevant quantities being equal.

It seems most probable that, in marine air, the initially largest cloud droplets will form on the largest sea-salt nuclei, as shown by the detailed study of the condensational growth rates of sea-salt nuclei which was made by Keith and Arons (4). The number of these large salt nuclei at cloud levels is known to vary greatly (15)(16). Hence, in an area where the cloud height, liquid water content, air stability, etc., are relatively constant, it was thought that the amount of rain falling might be related to the number of large salt nuclei in the air.

Ideas such as those sketched above led the first author to make measurements of airborne sea salt in Hawaii, where U. S. Weather Bureau problems of forecasting shower rains had suggested that some parameters, other than those routinely measured, might be involved in the rain-forming process (1). It was felt that Hawaii would be a favorable place to test the rain-salt hypothesis, since the trade-wind inversion tends to limit cloud

growth, producing more uniform cloud heights. As a consequence of the collaboration of the second author, an extensive study of the distribution of sea-salt particles was made from aircraft over the sea on the windward side of the island of Oahu. An attempt is made here to relate the quantity of airborne salt, which was usually sampled once a day, to the total amount of rain which fell on the island during each twenty-four hour period and to cloud height, which is represented by the cloud-base-to-inversion distances. These and other observations are presented in Table I and are discussed in sections 1, 2, 3, and 4 below.

Other observed properties, such as mixing ratios, wind shear, instability, etc., which are potentially related to rainfall, are discussed in sections 4 and 5, though they are not used directly in this exploratory study. These additional data are included here in Table I so that other workers may examine their relevancy to the problem.

1. Airborne salt particles

The sampling of the salt particles was by impingment upon small glass slides, which were exposed from aircraft. The slides were then taken to the laboratory, where diameter measurements and counts were made with a microscope at a relative humidity of 90%. At this relative humidity all nuclei are droplets, and the weights of salt in the individual droplets were readily computed from the droplet diameters. The detailed description of the techniques used to sample and measure the minute atmospheric salt particles has already been published (14)(15) and will not be discussed further in the present paper.

On each flight an attempt was made to obtain the salt-nuclei samples at an altitude which was about one-hundred meters less than the altitude of the bases of the scattered local cumulus clouds. The sampling position was

over the sea and several miles up-wind (NE) of the island of Oahu (see Fig. 1). The air around and below the bases of the clouds had a higher water vapor content than was found at greater altitudes in the cloud layer. It is supposed here that it is this lower air and its' salt aerosols which flows into and forms the clouds. Thus the attempt here is to relate the quantities of the large salt aerosols present in the sub-cloud layer of air to the rain which subsequently falls from clouds developed above as the air flows over the island.

Columns 3 and 4 of Table I show the salt amounts sampled on fifty-two flights, which were made on forty-two different days during 1951 and 1952. The quantities in these columns are limited to salt particles larger than 120×10^{-12} grams. This limit is due to the fact that on many of the sampling days, and as a labor-saving step, only the larger nuclei on the sides were counted.

2. Total rainfall measurements on Oahu

Daily readings of many gages, scattered over the windward and central portions of the island, were used in drawing isoheytal maps for each of the forty-two days on which salt sampling flights were made. An example of these maps is shown on Figure I. The rain data were assembled and the rain maps drawn by the second author, quite independently of the salt-nuclei-sampling activities of the first author.

Column 2 on Table I shows the values for total rainfall on Oahu, which were derived by planimeter-area measurements on the isoheytal maps. For instance the total rainfall obtained from the map shown in Figure I is 6×10^6 metric tons, a value derived by summing the products of the areas and the average rainfall amounts in each isoheytal contour. The rain amounts

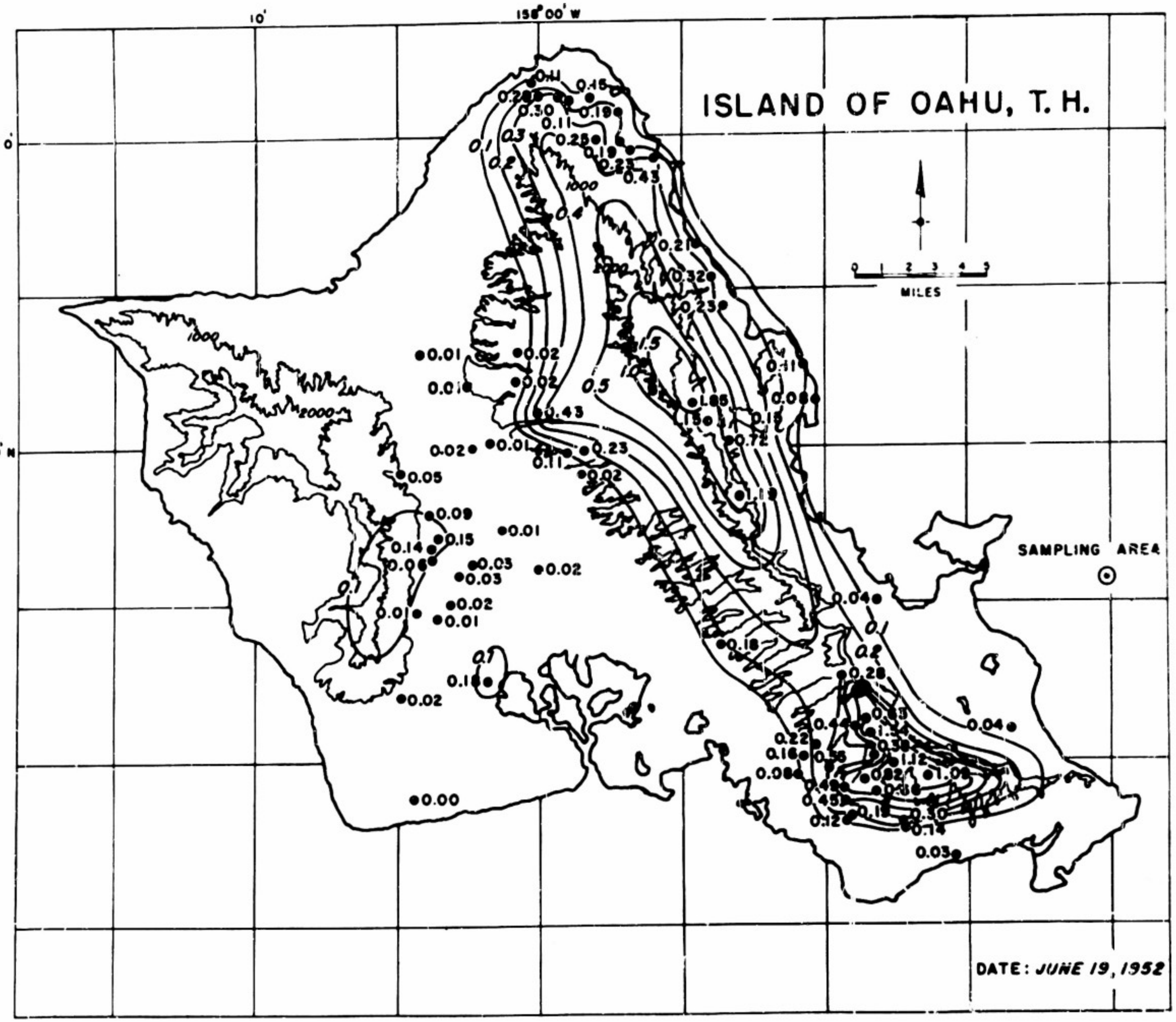

FIGURE 1. EXAMPLE OF ISOHEYTAL MAPS USED IN DERIVING THE TOTAL RAIN AMOUNTS SHOWN ON TABLE I, COLUMN 2. RAINFALL AMOUNTS ARE GIVEN IN INCHES.

TABLE I

Observations arranged in chronological order

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Date	Total daily rainfall	Salt nuclei number ℓ^{-1} of air	Salt nuclei weight m^{-3} of air	Cloud-base to-inversion distance	Wind shear 915 - 1830 meters	Av. wind speed at cloud levels	Wind force	Av. wind direction at cloud levels	Mixing ratio near cloud-base altitudes	Mixing ratio in clear air at 1525 m (from radio-sonde)	Mixing ratio in clouds at 1525 m	Instability; cloud-base-to inversion	Time of sampling flights	Minimum cloud-base altitude
	unit=10^6 m^3	>120 $\mu\mu$ gm	μ gm	m	m sec^{-1}	m sec^{-1}		° true	gm/kg	gm/kg	gm/kg	cm^2	LCT	m
4 Jun 51	0.4	3.2	1.1	1700	2.0	5.7	3	57	13.0	7.8	12.1	1.42	13	640
5 Jun 51	0.8	4.7	1.4	1550	4.3	6.7	3.5	74	13.9	8.2	12.5	1.67	14	610
11 Jun 51	1.4	13.5	6.3	1360*	5.3	9.3	5	79	13.0	7.3	12.3	0.58	14	655
12 Jun 51	2.6	5.3	1.8	1920	3.0	8.2	5.5	71	12.8	7.1	12.3	1.55	11	580
13 Jun 51	0.8	18.6	6.0	1550	6.0	7.2	4	62	13.0	8.8	13.0	1.42	14	550
14 Jun 51	1.9	8.7	3.4	1260	2.6	11.3	4.5	70	13.6	9.1	13.2	1.03	10	560
15 Jun 51	3.7	11.5	5.0	1370	-	8.2	4.5	71	14.1	9.7	12.8	1.22	15	460
16 Jun 51	1.1	8.4	3.6	1160	3.2	9.3	4.5	65	13.6	9.6	12.3	1.16	10	510
17 Jun 51	0.8	6.1	2.0	1130	4.3	5.7	4	63	13.5	10.4	12.5	0.84	11	610
18 Jun 51	0.1	1.9	0.4	1100	3.0	3.1	3	74	13.7	10.8	13.4	0.65	14	640
19 Jun 51	0.3	3.2	1.0	1400	2.7	2.1	4	78	14.9	9.0	13.5	0.90	12	510
20 Jun 51	0.5	1.5	0.4	>3000*	3.4	2.1	3	variable	14.5	7.2	13.2	--	08	460
26 Dec 51	2.7	3.7	1.2	2710*	4.3	7.2	3.5	83	12.2	7.2	11.5	1.35	14	700
27 Dec 51	2.3	2.7	1.0	2850	2.1	4.6	4	61	12.2	6.5	11.7	1.22	11	560
28 Dec 51	1.5	1.0	0.3	2220	4.0	6.2	3	65	11.2	8.0	11.4	0.77	10	400
29 Dec 51	6.0	7.4	3.8	>3000*	5.6	5.7	5	88	11.3	8.5	12.0	--	14	855
2 Jan 52	3.5	4.5	1.5	>3000*	3.8	9.3	3.5	86	15.6	10.3	13.5	--	09	335
3 Jan 52	9.9	11.3	8.1	>3000*	3.8	11.8	6	89	14.4	9.5	12.4	--	09	460
4 Jan 52	0.6	21.5	16.4	425*	3.5	8.2	7	89	13.2	8.3	11.3	0.13	11	580
5 Jan 52	trace	18.0	13.0	305	4.2	10.3	7	95	8.1	6.0	10.2	0.19	10	940
8 Jan 52	11.0	12.1	4.9	2130	4.3	9.8	5	99	12.0	8.7	11.5	0.90	14	610
9 Jan 52	8.7	25.9	16.2	2090	4.7	12.9	6	83	12.5	10.5	12.0	0.90	15	655
11 Jan 52	6.7	23.3	13.2	2330*	8.2	17.0	7	90	10.6	5.2	11.1	2.12	10	870
12 Jan 52	1.2	47.0	31.0	730*	9.7	15.9	7	77	10.9	3.3	10.5	0.06	10	790
10 Feb 52	4.2	19.3	13.7	1830	4.7	13.9	6	94	13.0	9.4	11.7	0.39	11	510
15 Feb 52	3.5	0.3	0.1	>3000*	5.3	2.6	1	variable	13.8	8.1	11.0	--	14	510
20 Feb 52	0.6	2.9	0.7	975	4.6	7.7	4	64	8.7	6.4	10.5	0.32	15	580
25 Feb 52	2.6	11.7	7.0	1620	3.1	6.7	4.5	85	10.9	8.8	11.5	1.10	14	790
10 Mar 52	3.2	28.3	11.2	>3000*	4.2	12.9	5	74	11.5	7.3	11.0	--	14	685
22 Apr 52	1.9	10.3	4.2	1700	8.5	12.9	5	49	10.4	8.2	10.6	1.22	11	790
21 May 52	1.1	1.5	0.5	2200*	4.6	6.7	3	86	13.7	9.0	11.8	1.68	15	460
30 May 52	0.4	9.5	3.0	1130	4.0	9.8	4.5	77	12.6	6.8	12.3	1.29	14	640
16 Jun 52	3.7	16.9	6.5	1830	6.8	5.7	5	55	12.8	8.7	11.9	0.84	11-16	610
17 Jun 52	3.2	7.5	2.3	1980	5.0	6.3	3.5	78	11.6	9.2	12.5	2.38	10-16	700
18 Jun 52	6.0	9.0	4.1	2440	3.3	9.8	4	80	14.0	9.7	13.0	2.38	10-16	245
25 Jun 52	0.1	9.9	3.7	1190	3.3	10.8	4	90	13.2	7.2	12.2	1.42	10-16	610
26 Jun 52	4.0	10.9	3.3	1630	4.6	11.3	3.5	80	13.9	7.7	12.5	1.35	10-16	530
27 Jun 52	4.3	15.8	6.1	1720	-	11.3	4	73	15.0	7.8	13.0	1.35	10-16	440
28 Jun 52	2.7	12.3	5.3	1620	3.5	11.3	4.5	75	13.5	8.1	12.7	0.97	10-16	520
29 Jun 52	4.3	8.9	3.2	1920	4.8	5.7	4	81	13.0	10.6	13.1	0.97	10-16	670
30 Jun 52	1.3	5.1	2.0	1740	3.5	8.2	3.5	46	12.8	9.9	13.4	0.97	10-16	610
1 Jul 52	2.7	4.3	1.3	2160	3.1	9.3	3.5	88	13.7	8.9	12.9	2.00	10-16	550

indicated on Table I were, in each case, collected in the time interval from 0800 LCT of one day to 0800 LCT of the following day. The date of the Hawaiian rain records is that of the day when the gages were read. In using these records here, however, it should be noted that the date of the preceeding day is used; that is, the date when the salt nuclei sample was taken. Thus the rainfall amount of 6×10^6 metric tons taken from the isoheytal map for 19 June 1952 (see Fig. I), is listed on Table I as occurring on 18 June 1952.

3. Inversion altitude and cloud-base-to-inversion distance

The cloud-base-to-inversion distance for each twenty-four hour period was taken from pseudo-adiabatic charts of the Honolulu radiosonde records, using the soundings showing the maximum inversion altitudes observed at 0500 (LCT). For example, the 20th value in column 5, Table I is based upon the radiosonde record of 0500 LCT on 6 February 1952, whereas the 20th rain record (column 2) is for the period 0800 LCT, 5 February 1952 to 0800 on the 6th. If the 0500 sounding of February 5 had revealed a higher inversion, then this sounding would have been used in deriving the first value in column 5. This selection of the higher inversion altitude measured at the 0500 soundings will be discussed later.

The 1700 LCT radiosonde temperature records were not used here because of the marked evidence on many days of local heating over the island which extended up to cloud heights, as shown on Figure 2, B. Thus it is thought that the 0500 soundings more nearly represent conditions over the sea and over the windward parts of the island where most of the rain falls.

The minimum cloud-base altitude measurements (column 15) were used to mark the point where cloud temperatures would depart from the dry lapse rate curves of the Honolulu soundings. This is illustrated in Figure 3.

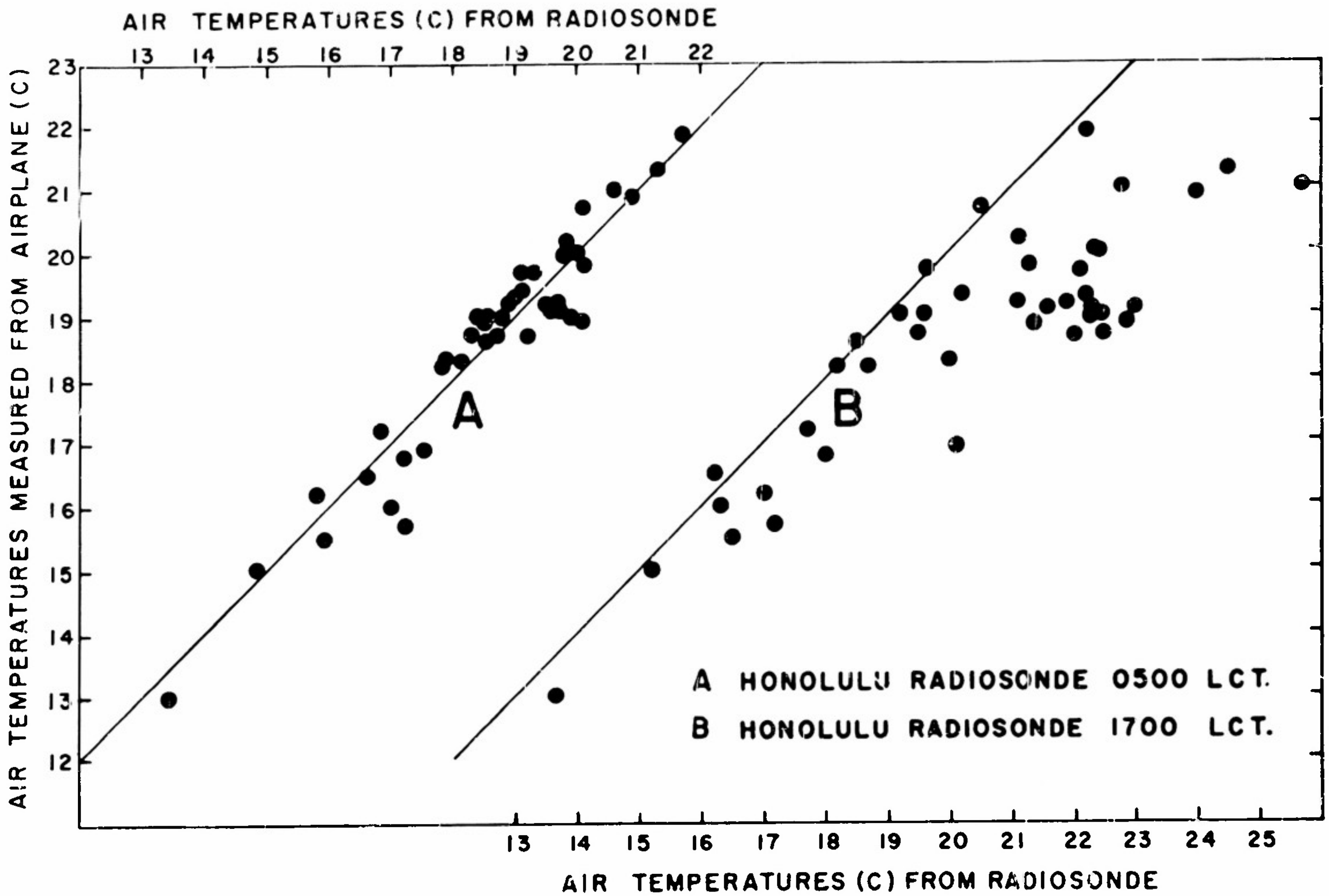

FIGURE 2. COMPARISON OF DRY-BULB TEMPERATURES OBSERVED FROM AIRCRAFT OVER THE SEA (SEE SAMPLING AREA, FIGURE 1), WITH HONOLULU RADIOSONDE TEMPERATURES OBTAINED ON THE SAME DAY AND AT COMPARABLE ALTITUDES.

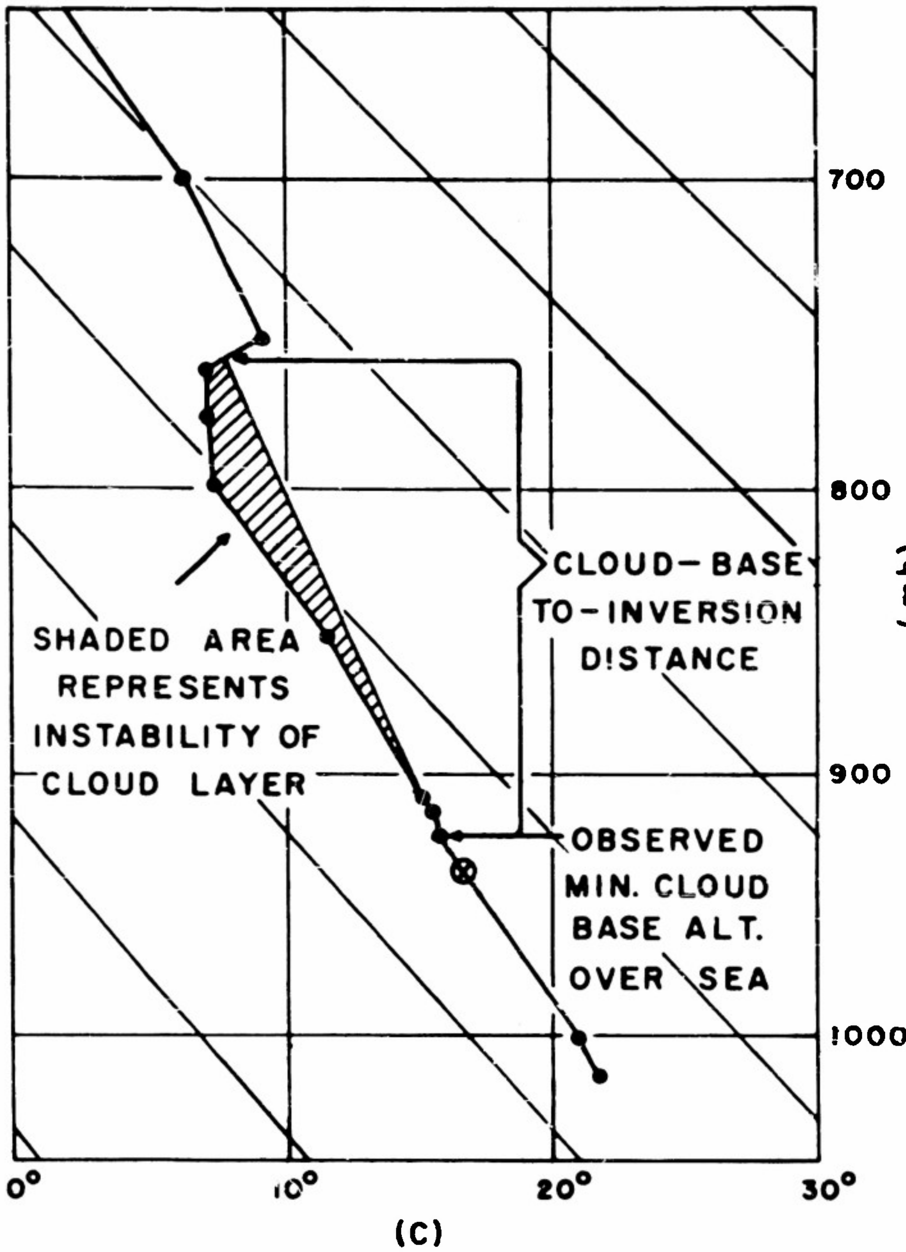

FIGURE 3.

PSEUDO-ADIABATIC CHART OF HONOLULU RADIOSONDE RECORD (1500Z, 26 FEBRUARY 1952). ILLUSTRATING DERIVATION OF THE CLOUD-BASE-TO-INVERSION DISTANCES AND THE INSTABILITY AREAS, SHOWN ON TABLE I, COLUMNS 5 AND 14. THE CIRCLED X MARKS A TEMPERATURE AND PRESSURE OBSERVED ON THE SAME DAY FROM AIRCRAFT OVER THE WINDWARD SEA.

The point at which this cloud-lapse curve, or wet adiabat, intersects the dry bulb temperature line on the chart is taken as the altitude of the cloud tops. Cloud-base-to-inversion distance (column 5) is then simply the altitude of this intersection point minus cloud base altitude, and is thought to represent roughly the maximum size of the clouds to be expected.

On those days when no temperature inversion occurred, the cloud wet-lapse line usually intersected the radiosonde temperature line in a near-isothermal region. In Table I, column 5, the asterisks mark the days when the inversion was not present. On six of these days the altitude of the intersection of the lapse rate lines exceeded 3,000 m. In column 5 the cloud-base-to-inversion distances for these six days are given as >3,000 m.

The reason for selecting minimum cloud base altitude and maximum inversion altitudes for deriving the daily cloud-base-to-inversion distances, was the thought that these conditions would favor cloud growth, and that rain occurring during each 24 hour period would be most likely to occur during the periods of greatest potential vertical extent of the clouds. These distances are, however, somewhat uncertain, due to the question of how many hours any observed inversion or cloud base altitude may persist. This question is discussed in some detail later.

In deriving cloud-base-to-inversion distances, possible effects of the diurnal variation of inversion height (Leopold, 6) are minimized by the consistent use of the 0500 LCT soundings only.*

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* One exception to this rule was made on January 11, 1952, when a 1900 LCT sounding was used. This sounding, made one hour after sunset, showed none of the diurnal heating indications evident in most of the 1700 LCT soundings.

4. Winds and cloud-base altitudes

The wind force at the sea surface was judged from the aircraft during sampling flights and is largely based upon the number, size and appearance of white caps, or breaking waves. The average wind speeds and directions at cloud levels, at 915, 1220, 1525, and 1830 meters, were taken from the records of the U. S. Weather Bureau at the Honolulu Airport, where winds aloft were measured at six-hour intervals. These wind velocities are given in columns 7 and 9, Table I.

The cloud-base altitudes shown in column 15, Table I, were measured from the airplane, and in each case they represent the minimum altitude observed during a flight period of about one hour. The position near which these airplane observations were made is shown on Figure I.

5. Wind shear, stability and mixing ratios

Among the various factors tending to reduce cloud growth and rain formation, the amount of shear present in the air through which the clouds must develop was thought to be of considerable importance (8). Other factors, such as the instability of the clear air in the cloud layer and the difference in mixing ratio between the cloud air and the environmental air, were also thought to be of importance here. Values representing wind shear, instability and mixing ratios are given on Table I, columns 6, 10, 11, 12 and 13.

The wind shear data are based on the Honolulu upper wind reports. The two reporting levels which seemed most appropriate were 915 m and 1830 m. The magnitude in m sec^{-1}, of the vector velocity shear between these two levels is given in columns 6, Table I.

The instability of the air is derived as illustrated on Figure 3, and is expressed in arbitrary units of 1 cm^2 on the pseudo-adiabatic chart, as shown in column 13. Wet adiabatic ascent of the cloud is used, assuming no mixing with environmental air.

The mixing ratios shown in column 10, Table I, were determined from wet and dry bulb thermometer readings made from aircraft (air speed 29 m sec^{-1}) at the altitude and time when the salt-particle samples were taken. Small corrections for thermometer error were applied. The mixing ratio values shown in columns 11 and 12 were taken from the pseudo-adiabatic charts of the 0500 LCT Honolulu radiosonde observations (see section 3 above). Cloud mixing ratios (column 12) were derived from these charts through the use of the observed minimum cloud base altitudes over the sea (column 15), assuming that the temperature at cloud base was the same as that given by the Honolulu radiosonde. A comparison of dry bulb-temperature measured from the airplane with the temperatures taken from the Honolulu radiosonde records is shown in Figure 2.

6. Relating cloud-base-to-inversion distance, salt particles, and rainfall

Assuming that cloud-base-to-inversion distance and the number of salt particles might be the major factors causing variations in total rain amount, these three variables were plotted as shown on Figure 4.*

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* The only data excluded from Figure 4 are those obtained on the five days when winds at cloud levels averaged less than 5 m sec^{-1} (see column 7, Table I). The reason for this exclusion is that low wind conditions favor a marked development of convective activity over the island during the daylight hours, thus making it more unlikely that the cloud-base-to-inversion distances, derived from the 0500 radiosonde temperature record, will represent the maximum cloud heights developed during the day.

The rainfall amounts on four of the six days when the cloud-base-to-inversion distance exceeded 3,000 meters, are simply plotted slightly above the maximum ordinate value (3000 m) given on Figure 4.

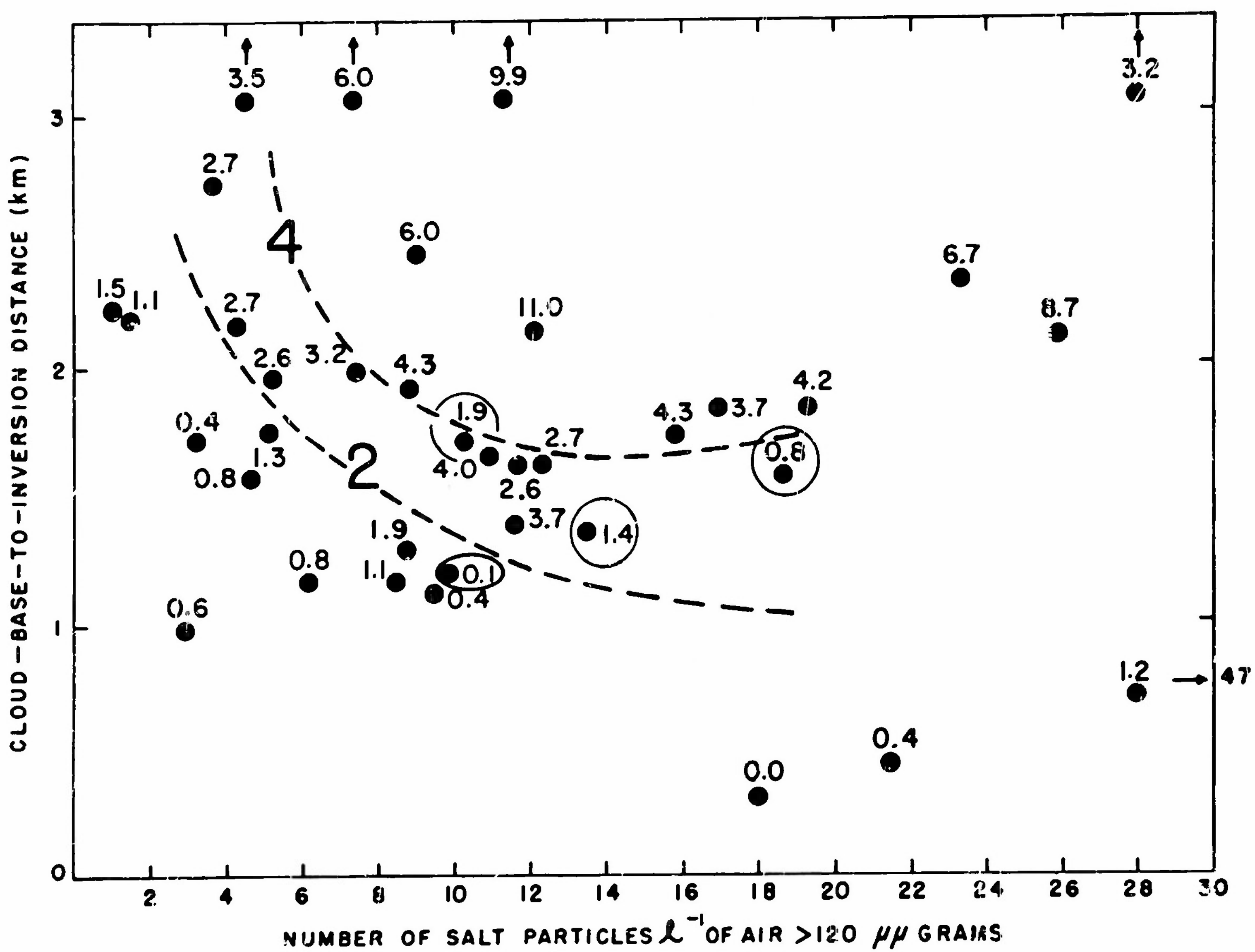

FIGURE 4. TOTAL DAILY AMOUNTS OF RAINFALL ON OAHU, EXPRESSED IN UNITS OF 10^6 METRIC TONS, RELATED TO THE NUMBERS OF SALT NUCLEI IN THE AIR AND TO THE CLOUD-BASE-TO-INVERSION DISTANCES. SEE TEXT FOR FURTHER DISCUSSION.

The dashed lines on this figure are intended as an aid to the eye in roughly separating the values of rain amount into those less than two, those between two and four, and those greater than four.

The most seriously divergent exceptions to the isoheytal pattern suggested by the dashed lines on Figure 4 are the four rainfall amounts which are enclosed in circles. These exceptional observations will be discussed later. At the present time it is sufficient to point out that, with the above exceptions, the data on Figure 4 may be interpreted as indicating a crude quantitative relationship of the rainfall to the other variables on about two-thirds of the graph. For instance, note that increased values of cloud-base-to-inversion distance and of salt nuclei number are generally attended by increased rainfall amounts, with a faint suggestion of an optimum rain amount in the middle range of nuclei number. On the right-hand portion of the figure the data are too sparce to justify an extension of the dashed isoheytal lines.

As shown on Figure 5 and in an earlier paper (16), the number of salt particles tends, however, to increase as the winds become stronger. Thus one might reasonably ask to what extent wind speed may contribute to rainfall. As a first test of the possible relationship of wind to rainfall, wind speed at cloud levels (see Table I, column 7) was substituted for salt particle number on a diagram similar to Figure 4. The resulting distribution of values for rain amount is shown on Figure 6, and is clearly considerably less systematic than the distribution shown on Figure 4. Does this mean that wind has less effect upon rain in Hawaii than does the salt nuclei?

In many of the previous studies of Hawaiian rainfall it has been pointed out by other authors that it is reasonable to expect increased rainfall with stronger winds, since these winds transport more moist air over the mountains.

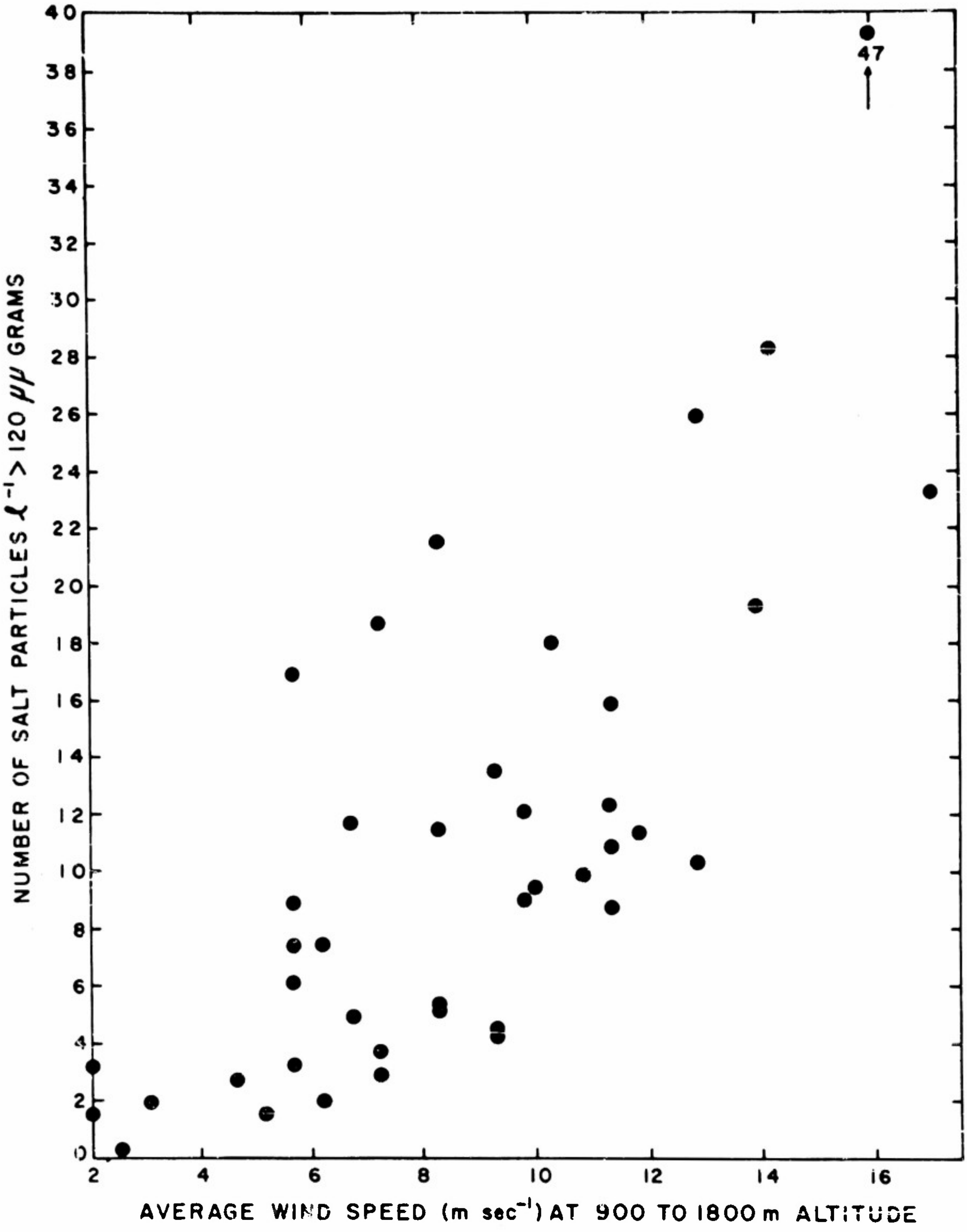

FIGURE 5. NUMBER OF SALT PARTICLES, NEAR CLOUD-BASE ALTITUDES, RELATED TO THE AVERAGE WIND SPEED AT ALTITUDES BETWEEN 900 AND 1800 METERS. (SEE REFERENCE 6 FOR MORE DETAILED INDICATION OF DEPENDENCE OF SALT NUCLEI UPON WIND).

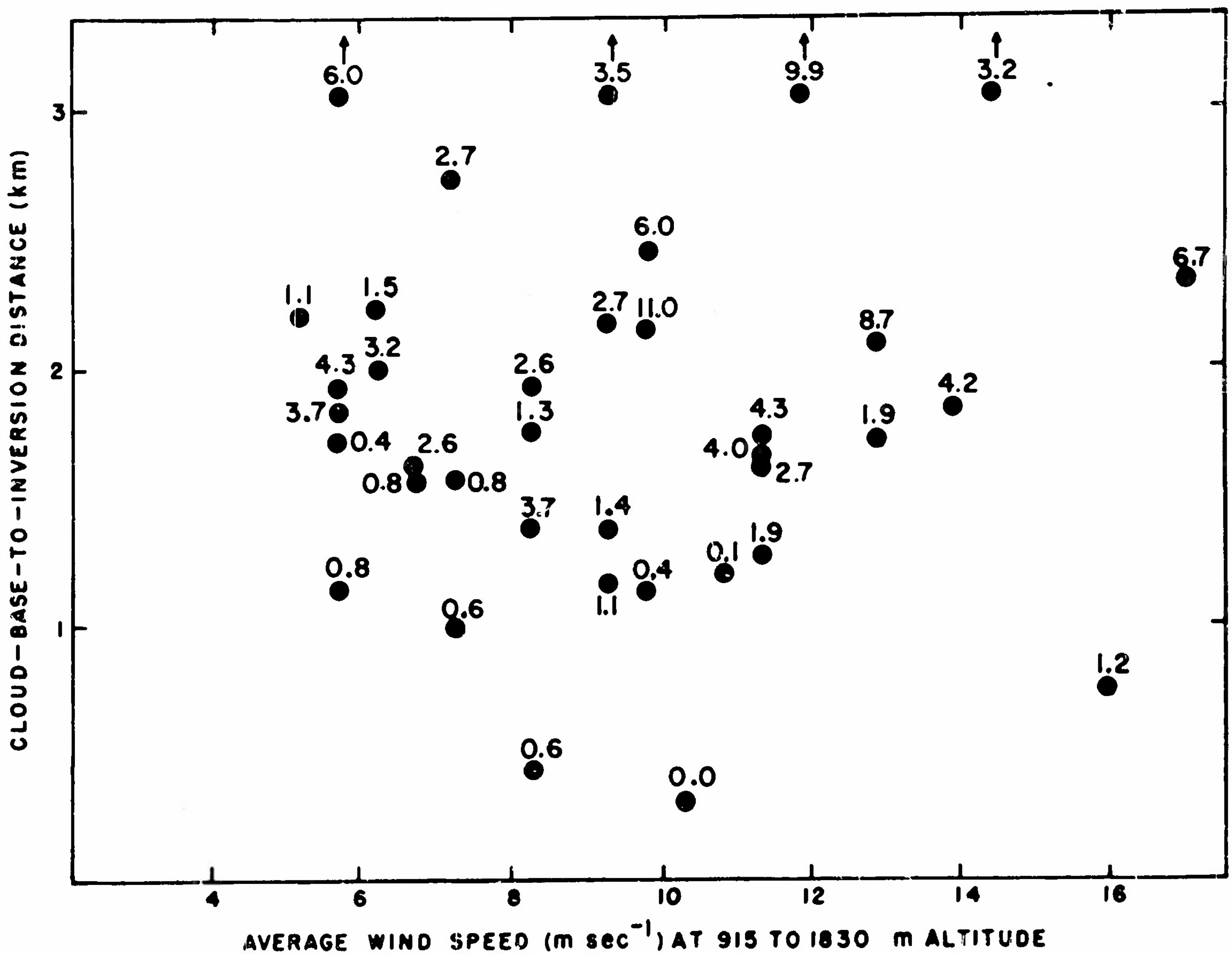

FIGURE 6. REPETITION OF FIGURE 4, SUBSTITUTING WIND SPEED FOR NUMBERS OF SALT PARTICLES.

The amount of water vapor moving over the island daily should be nearly a linear function of wind speed, other factors remaining constant. Assuming that rainfall also might be a linear function of wind speed, the rainfall values plotted on Figure 4 were divided by the ratios of the observed wind speeds to the minimum wind speed of 5 m sec^{-1}. The resulting modified rain amounts are shown on Figure 7. It is interesting that the general pattern of distribution of rain amount shown in Figure 4 is still evident in Figure 7. In other words, increased values of cloud-base-to-inversion distance and of salt nuclei number are still generally attended by increased rainfall amounts. Does this mean that the remaining pattern of change in rain amount with different values for salt nuclei number is due to the affects of salt nuclei on rainfall?

Discussion

The above questions cannot be answered at this time. The salt aerosols from the sea probably add still another variable to the already complex problem of Hawaiian rainfall. The contribution of wind to the daily rainfall in Hawaii remains unknown (13) and there is at the present time little justification for assuming that rainfall might (or might not) be a simple linear function of wind velocity, as was done in producing the "modified rain amounts" given on Figure 7. Further more detailed measurements are needed. The primary usefulness of the present study is that it further excites the curiousity about the role of salt neclei in rain formation and it leads reasonably to pertinent suggestions about where, when and how future measurements should be made in an attempt to separate the wind and salt-aerosol contributions to rainfall.

In thinking about the possible significance of the distribution of values shown on Figure 4, it is well to remember that the twenty-four hour

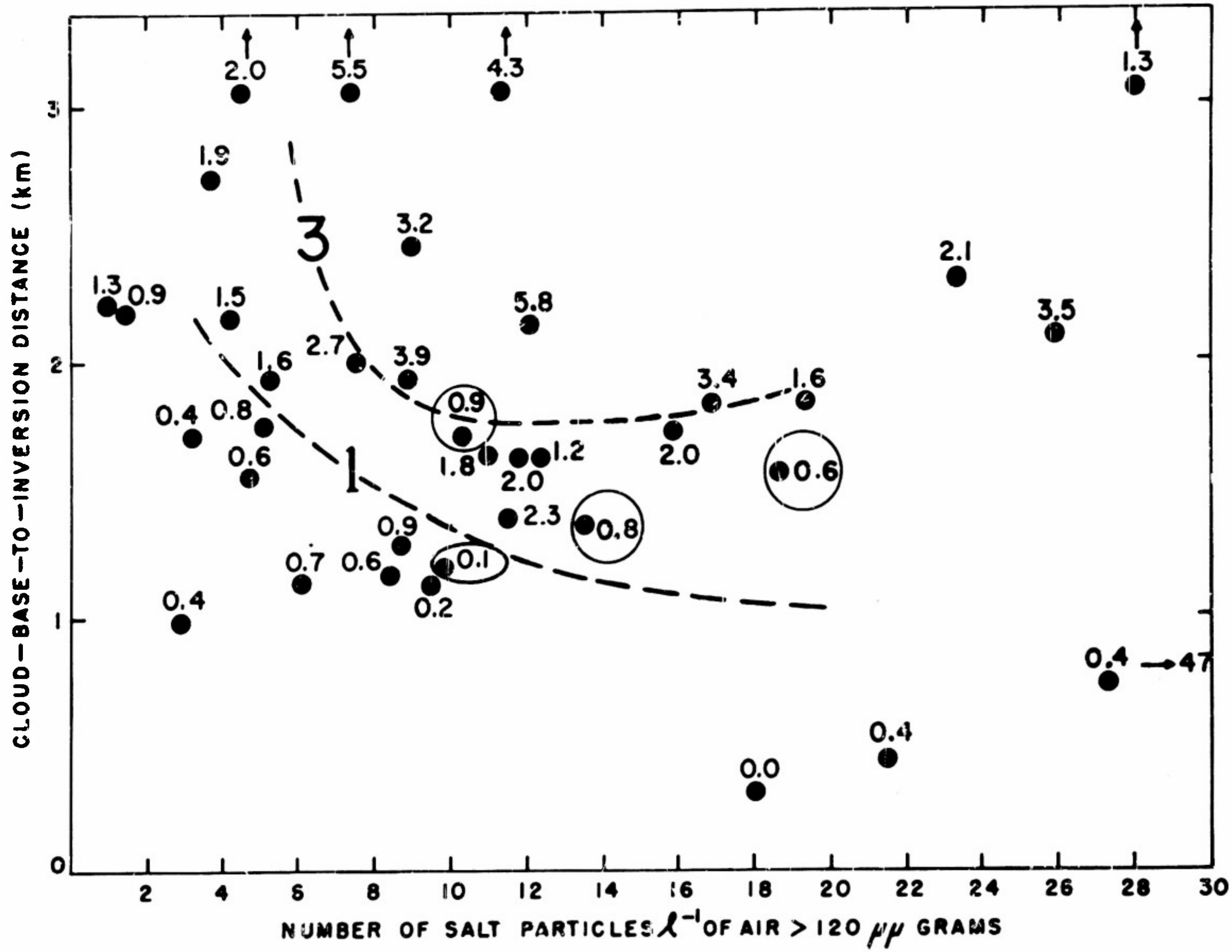

FIGURE 7. THE QUOTIENT OF THE TOTAL DAILY RAIN AMOUNTS AND A FUNCTION OF WIND SPEED, RELATED TO THE NUMBER OF SALT NUCLEI IN THE AIR AND TO THE CLOUD-BASE-TO-INVERSION DISTANCES. SEE TEXT FOR FURTHER INFORMATION.

rainfall amounts represent an island-wide integration, whereas the values for number of salt particles and for cloud-base-to-inversion distances were usually taken from measurements obtained only once or twice a day and during relatively short periods of time. The proportion of each of the twenty-four hour periods during which these later values actually existed in the air over the island is of course unknown.

Changes in inversion height of as much as 1000 m within a few hours have been indicated by Leopold (6), and are occasionally evident in the Honolulu radiosonde records used in the present study. These changes will, of course, add uncertainty to the ordinate values on Figure 4, since these values are derived from the radiosonde records as described in section 3.

The usefulness of the cloud-base-to-inversion distances as a measure of cloud thickness and rainfall potential, probably depends upon the comparability of the duration times of these distances on the various sampling days. There is no adequate information about the hours of duration of any specific cloud-base-to-inversion distance, nor of the extent to which this duration is comparable from one sampling day to the next. In the absence of this information, further discussion of this point does not seem to be useful. It should be remarked however that Figures 4 and 7 suggest strongly that the cloud-base-to-inversion distances determined on the various days are related to the rainfall. This result implies that the durations of these distances are, on the average, sufficient to markedly influence the rainfall during each twenty-four hour period.

The amount of airborne salt also varies considerably during short periods of time. On ten of the days represented on Table I and Figures 4, 6 and 7, counts of salt nuclei were obtained at 1000 and 1600 hours, instead of

the usual single observation per day. An average of these salt-particle counts is used in Figures 4 and 7. The ratios of the maximum to the minimum of these two values for salt nuclei number, averaged 1.56. On each of the remaining 27 days, when only one observation was made, the nuclei content of the air may have varied an equal amount.

Thus it is evident that the two important quantities cloud-base-to-inversion distance and salt nuclei number can be far from constant during a twenty-four hour period. It is thought that this lack of constancy may account for some of the observations which differ widely from the proposed pattern (see circled values on Figures 4 and 7). In view of the variability of the above quantities, it is rather surprising that there is any pattern at all to be seen in the values on these figures. The suggestion of a pattern in the data shown, despite the above variability, may be due to a real relationship between the quantities involved. It may be due also to an average relative constancy of the number of salt nuclei and cloud-base-to-inversion distance during a 24 hour period, as compared to the changes in these quantities occurring during longer periods of time. It is clear that numerous observations of all of the quantities involved are needed throughout each twenty-four hour period in order to properly test the reality of the rainfall pattern suggested by Figures 4 and 7. At this early exploratory stage of this study, it does not seem fruitful to speculate about the meaning of this precipitation pattern and what it may imply about the rain-forming mechanism.

It will be noted on Figure 3 that no consideration is given to the probable change in the slope of the cloud temperature-lapse line which would result from mixing of the cloud air with the environmental air during ascent. This mixing would tend to decrease the cloud top temperature and, as is evident from the gradient of salt nuclei number in the cloud layer as shown on Figure 8,

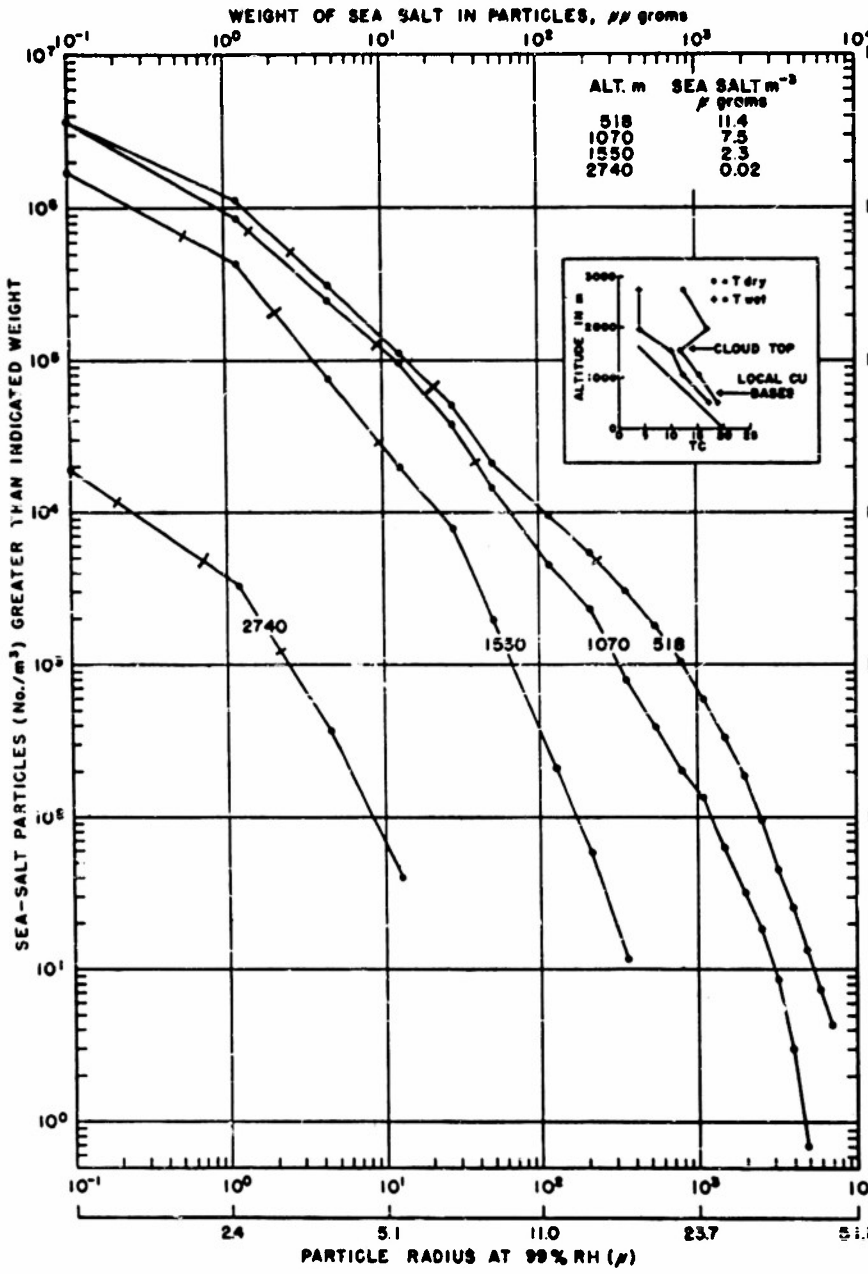

FIGURE 8.

AN EXAMPLE OF THE DECREASE, WITH ALTITUDE, IN THE NUMBERS OF SALT PARTICLES SAMPLED BELOW AND ABOVE THE INVERSION IN THE HAWAIIAN AREA. APPROXIMATE POSITION 21°30'N, 157°40'W; TIME 1300 LCT, 30 MAY 1952. SURFACE WIND 80 DEG. FORCE 4 TO 5. NOTE THAT THE REGION OF CLOUD DEVELOPMENT IS ONE OF RAPID DECREASE, WITH HEIGHT, IN THE NUMBERS OF THE LARGER NUCLEI.

would also cause a reduction of the number of salt nuclei in the cloud. The omission of consideration of these variables here is due to the impression that their effects upon the rainfall amounts is of secondary importance.

Solot (11) and others have pointed out that wind speed determines the rate of moisture flow over the islands of Hawaii, and thus directly affects rainfall intensity. Stidd (12) has recently found evidence of a correlation of rainfall with the pressure over certain areas of the North Pacific and he suggests that this correlation is due to the influence of stronger trade winds in increasing rainfall. The fact that the number of salt nuclei in the air increases with increasing winds, poses a problem concerning the detailed nature of the affects of wind on rainfall. To what extent is the rainfall due to the amount of moist air or clouds flowing over the mountains and to what extent is it due to the quantities of potential raindrop-forming nuclei which are in this air?

The salt nuclei show a persistent pattern of relationship to rain amount which is not revealed by wind speed and rain amount (compare Figures 4 and 7 to Figure 6). This apparent relationship of nuclei to rainfall may not be due however to quantitative effects of the number and size of salt particles upon the number and size of raindrops. It is possible that the determination of the number of the large salt nuclei in the air is a better measure of the 24 hour average wind speed over the sea and the mountains than are the Honolulu winds-aloft measurements. If this is true then Figures 4 and 7 may be interpreted as reflecting the wind effects upon total rainfall. The authors consider however that at the present stage of the study, these figures are clear evidence that salt nuclei will have to be considered in future studies of the Hawaiian rainfall problem.

Detailed short period studies, made during or immediately after rapid changes in wind speed, may supply an answer to this problem. It is expected

that the changes in the quantities of airborne salt at cloud levels will be found to lag behind the changes of wind speed, due to the time requirements for the upward diffusion of the salt particles in the case of increased wind, or for their sedimentation when the wind is reduced. The length of this time lag is uncertain however. If the lag proves to be long enough, say of several hours duration, it may be possible to answer the question of the contribution of salt nuclei to rain amount, through the use of measurements similar to those reported here which are closely spaced in time.

Does the rainfall on Oahu increase as the wind increases, or does the rainfall increase lag behind the wind for the length of time required for additional salt nuclei to be mixed upwards to the cloud levels? Conversely, does the rainfall decrease as the wind decreases, or does it tend to lag behind the wind decrease until sedimentation has caused a reduction in the number of nuclei?

Most of the shower rains which occur on Oahu are produced by cumulus clouds which are immersed in and drifting with the trade-wind stream. Many, if not most, of these clouds are formed before arriving over the island, and from some of them rain is falling as they approach the island from over the windward sea. This rain often continues to fall as the clouds pass over the windward beaches and move inland to the mountains. The time these clouds remain over the island is thus a function of wind speed at cloud altitudes.

One effect of greater cloud speed is of course to increase the number of clouds passing over the island in a given twenty-four hour period. If orographic lifting of clouds and of the ambient air accounts for the increased rainfall in the mountain areas, and this seems to be generally accepted (see references 6, 11, and 13), then the greater the number of clouds streaming over

the island in a day the greater the chances of rain formation. This pre-supposes, of course, that other rain-forming factors are equal.

However, since it is assumed that the Hawaiian shower rains are formed by accretional and/or condensational growth processes, which may be critically time-dependent, it is possible that high winds may move the clouds off the mountain areas before the rain-forming processes which bring about the rain excess in these areas, have time to proceed to completion. In this case one might expect a tendency towards a reduction of rain amount as winds exceed some optimum speed. This speed may be regarded as one which will cause a maximum number of clouds to be lifted over a mountain area within a given time, the duration of the lifted state being sufficient for a completion of the accretional and/or condensational growth processes. It is thought that the rainfall and other data given here are not sufficiently numerous throughout the range of values given to indicate an optimum wind speed.

The authors are inclined to think that the increased rain amount which falls from the clouds behind the crest of the Koolau Mountain Range (see Figure 1 and reference 3) is due in large part to the modification, over the mountains, of shower clouds which form over the windward sea and drift down upon the island in the trade-wind stream. The night maximum of orographic rain on Oahu, which has been noted by Leopold (6) and others, may be due to a night maximum of cloudiness over the sea (10). Thus a night maximum of rainfall does not necessarily suggest a night maximum of nuclei or wind speed, as might be supposed from the present study.

Yeh and others (17) have suggested that wind direction will affect the rainfall on Oahu, due to the fact that the flow is sometimes parallel to the mountain ridges and sometimes normal. As can be seen in column 9, Table I,

and on Figure 1, the average winds were nearly normal to the Koolau Range during most of the days represented here. This relative constancy of the wind has caused us to ignore direction as one of the variables possibly affecting rainfall in this series of days.

Remarks about further study

In order to make a further test of the relationship of salt particles and/or wind to Hawaiian rainfall, it seems to be necessary to make additional measurements from aircraft. These measurements should be made over the sea, several kilometers directly upwind from the high-rainfall area on Oahu, and should include as many of the variables as possible. Four or more flights a day would be desirable, especially after a time of rapid change in wind speed.

An increase in the number of recording rain gages along the Koolau Range would add to the accuracy of the isoheytal maps. As shown on Figure 1, there are rather large areas in the high-rainfall regions of the mountain range where there are no gages. This relative sparcity of gages in this region adds a considerable uncertainty to the drawing of the isoheytal lines and hence to the total rainfall values derived from the maps. Errors due to this uncertainty add another factor to be considered in the evaluation of Figures 4, 5 and 7.

If further study confirms and expands the general pattern of rainfall distribution suggested on Figures 4 and 7, the question of the day-to-day forecast value of the measurements used in deriving this pattern will arise and it will become necessary to seek an explanation of the result in terms of the detailed mechanics of raindrop formation.

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